High Fidelity VSF Measurements and Inversion for RaDyO (Hi Fi RaDyO)

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LONG TERM GOALS

Time and space dependent radiance distributions at the sea surface are a function of the shape of the incident distribution on the surface, modification by the sea surface itself from topography and transmission characteristics, and alteration by the Inherent Optical Properties (IOPs) of the surface ocean. The long term goal of the proposed work is understanding this last controlling factor. With a knowledge of the IOPs, radiance fields can be directly computed from the incident field using the equation of radiative transfer, now embedded in commercially available code (e.g., Hydrolight).

With the state of current technology and methodologies, the primary obstacles in understanding subsurface IOPs and their high-frequency dynamics are a lack of 1) volume scattering instrumentation, 2) comprehensive inversion models linking the IOPs with the causative bubble, particulate, and dissolved matter in the water (which in many cases will require input dependent on 1), and 3) suitably stable, non-intrusive platforms to sample the subsurface ocean. The first two challenges are addressed in this project.

OBJECTIVE

There are two overarching objectives for this project:

1) To develop an in-situ volume scattering function device measuring volume scattering from 10° to 170° at 10° intervals and sampling rates of 1 s^{-1} or better to sample the VSF in near-surface waters; and

2) To develop and refine IOP inversion models to resolve particle field characteristics on small spatial (cm’s) and temporal (<1 s) scales in near-surface waters.

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APPROACH

Our design for the VSF device is illustrated in **Figure 1**. The device is called MASCOT (Multi-Angle SCattering Optical Tool). The source beam is a 30 mW 650 nm laser diode expanded with a Gallilean 2X beam expander to an approximately 3mm X 8 mm elliptical shape. A wedge depolarizer is used to provide the unpolarized light needed for VSF determinations. Seventeen independent silicon diode detectors spaced in a semicircle 10 cm around the sample volume measure volume scattering from 10° to 170° at 10° intervals. The total pathlength for all scattering measurements is 20 cm. Independent detectors allow resolution of the VSF without any moving parts and time-consuming scanning. Additionally, each detector can be optimized for its specific measurement. Detector field-of-views (FOVs) range from 0.8° to 5° for the different detectors, with the narrowest FOVs associated with the detectors measuring scattering in the forward direction. Using proprietary electronics, a 20 Hz sampling rate for all channels has been achieved while maintaining a worst case signal:noise of 300:1. Relatively fast sampling rates are important in resolving VSFs in the highly dynamic ocean subsurface.

MASCOT calibration parameters have been derived in solutions of microspherical beads and the particle standard Arizona Road Dust (AZRD; Powder Tech. Inc.). A reference detector may be used to account for any fluctuations in source intensity. Coincident measurements of beam attenuation are required to correct for light losses along the optical path of the scattering measurements (all pathlengths nominally ~20 cm). Algorithms have also been contemplated that would account for attenuation without a separate direct measurement. The design in **Fig. 1** is made as small as possible while accommodating all necessary hardware, a criterion established in part to minimize this effect. Two MASCOT prototypes are being developed for redundancy in case a problem with a component arises. Two systems allows for concurrent testing of different sensor components.

For the inversion modeling, we will extend the capabilities of existing models (Twardowski et al. 2001; Twardowski and Zaneveld, 2004) by incorporating input from new VSF measurements and by adding bubble particle populations (clean and coated) in the models. At a minimum, we expect the inversion model will give us component concentrations and size distributions, with the components being organic particles (living+detrital), minerals, and bubbles. We expect to co-deploy the MASCOT and the commercially available near-forward VSF device LISST (Sequoia Inc.) in order to capture the VSF with good resolution from ~0.1 degrees to 170 degrees.

RaDyO field deployments are currently planned in collaboration with other RaDyO investigators off Scripps Pier in January 2008, in Santa Barbara Channel in September 2008, and off the Hawaii islands in May 2009. For these efforts, we plan to concurrently deploy CTD + AC9 (+ ACS) + MASCOT + LISST + ECO sensors in a real-time vertical profiling system (**Fig. 2)**. We also expect to integrate two additional sensors for these deployments: 1) a high sampling rate fish-eye lens radiometer currently being developed by Marlon Lewis and Scott McLean of Satlantic, and 2) a bubble acoustic resonator provided by David Farmer and Svein Vagle. For the Scripps Pier experiment, a mobile deployment platform will be configured so that measurements may be made along the length of the pier, with the expectation that higher concentrations of bubbles will be observed nearing the surf zone. For subsequent field work in SBC and Hawaii, we will deploy our sensor package off the R/V Kilo Moana.

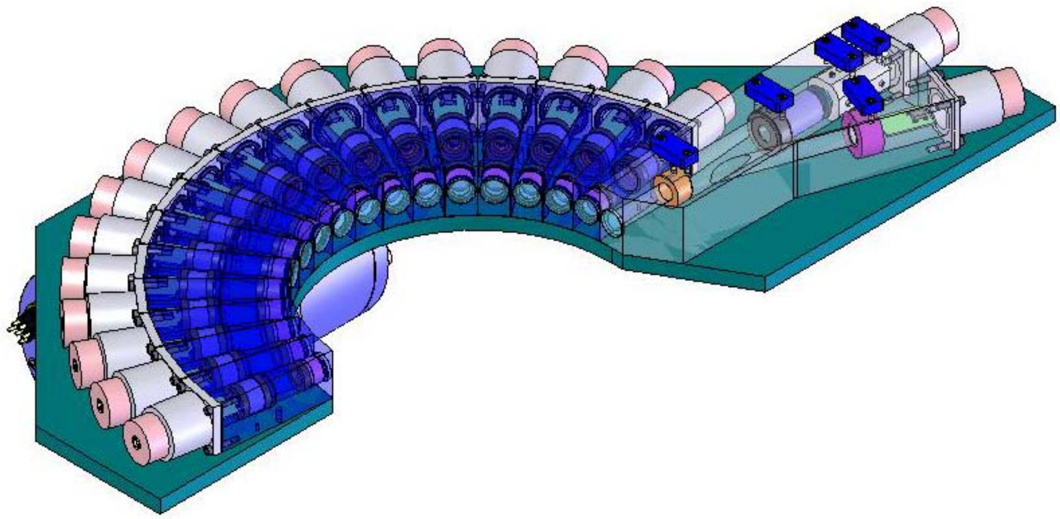

Figure 1. Oblique view illustration of the MASCOT. The VSF is resolved from 10 to 170 degrees in 10 degree intervals. Detectors are wedge shaped and arranged in a semi-circle on an aluminum frame to minimize reflections and perturbation of the water sample in the remote volume (center of semi-circle). The source assembly includes a 30 mW 650 nm laser diode, reference detector, beam expander, and wedge depolarizer. Wiring from all the detector modules and the source module feeds to a data handling unit.

WORK COMPLETED

- The first MASCOT prototype was completed in October 2006;

- A summary of calibration, field deployment, and data processing activity is provided in **Table 1** below;

Table 1. Timeline of MASCOT activity in FY07. Time after May 2007 has been devoted to calibration analyses and data processing.

OCTOBER	
	week of the 9th: delivery to WLE
	18-22: Deployment in Pen River, ME (observed bubbles)
DECEMBER	
	14-15: Calibration exercise; MASCOT and an AC9 in series of suspensions of Arizona Road Dust (AZRD) and microspherical beads of 1.992+/-0.025 um size.
JANUARY	
	rework at WL HQ: dark count offsets between air – water improved
FEBRUARY	
	6-7: Calibration exercise; MASCOT and an AC9 in series of suspensions of Arizona Road Dust (AZRD) and microspherical beads of 1.992+/-0.025 um size; this time with all WLE ECO BB sensors as well.
MARCH	
	First 2 weeks: Deployment in Hawaii (SORTIE)
	21-28: Deployment in northwest Atlantic (OCVAL: Endeavor)
MAY	
	4-10: Deployment in Hudson plume region (OCVAL)

RESULTS

Key results in FY07 were 1) the MASCOT prototype was fabricated, tuned and tested; 2) a viable calibration algorithm for the MASCOT was developed; and 3) a substantial body of field data was collected from several diverse water types around the world. **Fig. 2** shows the MASCOT device in a custom cage with additional optical sensors ready for deployment. Below is a description of the calibration method that was developed and some preliminary field results.

To calibrate each of the 17 raw signals to a volume scattering coefficient, $\beta(\theta)$ (m^{-1} sr^{-1}), a dark offset (DO) must be subtracted from the raw digital counts and the result multiplied by a scaling factor (SF). Dark offset variability improved after the January 2007 rework. The change in dark offset counts collected in air versus water ranged between 10% and 310% of the approximate count levels measured in the lab in a c=0.1 m^{-1} solution of the particle standard Arizona Road Dust (AZRD). A good target is a few percent for all channels. After the rework, the change in dark offset counts between air and freshwater ranged between 6% and 160% of these count levels. For all field deployments, dark offsets were measured in situ approximately daily. Standard deviations of the change in dark offsets in seawater within any cruise period were significantly better than the changes observed between air and water. As a percent relative to approximate count levels measured in the lab for c=0.1 m^{-1} AZRD, standard deviations were 33% and 35% worst case for the Hawaii cruises. This improved substantially for the North Atlantic cruise (9% worst case) and the Hudson cruise (1.7% worst case). The Hudson cruise was the only period where isolated battery power was used exclusively, and this presumably contributed to the excellent replicability in dark offsets. A conclusion is that working off battery power with a consistent sensor suite configuration can provide sufficiently reproducible dark offsets.

The relationship between MASCOT counts in any channel and the particulate scattering at 650 nm, bp650, is expected to follow:

$$[\text{COUNTS} - \text{DO}] = M * bp650 * \exp(- L * (cp650 * F + W)), \quad (1)$$

where DO is the dark offset, M is a linear slope that is related to relative gain, L is the pathlength (0.2 m), cp650 is particulate attenuation, F is the fraction of particulate attenuation that is applicable (i.e., we do not want to include the scattered light that is collected within the sample volume or detector aperture), and W is the pure water absorption (water scattering is assumed negligible) at 650 nm (0.34 m^{-1}). **Fig. 3** shows an example relationship between counts and cp650 (assumed approximately equal to bp650) for AZRD in one of the lab experiments. As attenuation increases, the rollover due to attenuation along the path is evident. Detector saturation at ~64000 digital counts (14 bit) is observed in some channels.

In Eq. 1, there are 2 unknowns, M and F. In theory, M and F could be solved for each channel using a least-squares minimization of residuals. There are relatively few experimental points, though, so errors can be expected to be high. However, we know that F should be approximately constant for all the channels (with the exception that 10, 20, 30, and 40 degree channels have narrower detector apertures). Thus, the normalized shape of each one of the channel regressions should be the same. We therefore solved for F by normalizing all of the channel regressions to area, essentially removing the slope (M) or gain effect. Using a least-squares minimization of the model in Eq. 1 to all the area-normalized data (included data from every channel) resulted in a value of 0.56 for F. Thus, approximately 44% of the attenuation effect is being removed by the collection of secondarily scattered light along the path by the sample volume and detector aperture.

If we invert Eq. 1 to solve for bp650, we obtain:

$$bp650 = [COUNTS - DO] / M * \exp(L * (cp650 * F + W)), \quad (2)$$

If the phase function of a particle solution is known, $P(\theta)$, we can then obtain $\beta(\theta)$:

$$\beta(\theta = [COUNTS - DO] * P(\theta) / M * \exp(L * (cp650 * F + W)). \quad (3)$$

The term [$P(\theta)$ / M] is the scaling factor (SF). For microspherical bead solutions, values of $P(\theta)$ can be determined theoretically using Mie theory and values of M can be determined experimentally. With F in hand, we solved for M individually for each channel using a least-squares minimization of the model in Eq. 1. This was carried out with a series of microspherical bead solutions for which the phase function may be computed from theory.

The weighting functions of the 17 MASCOT detectors were computed analytically using code written by Ron Zaneveld and are shown in **Fig. 4**. These weighting functions convolved with the P calculated for the beads are shown in **Fig. 5**. Scaling factors for each channel were then computed by dividing these $P(\theta)$ values by the experimental M values.

Applying the calibration derived SF and F parameters, along with measurement-specific DO's and cp650, $\beta(\theta)$ computed using Eq. 3 for the different suspensions from the AZRD experiment are shown in **Fig. 6**. ECO VSF measurements calibrated during the same bead experiment show very good agreement. Applying the calibration derived SF and F parameters, along with measurement-specific DO's and cp650, calibrated $\beta(\theta)$ obtained with the MASCOT in Hawaii onboard the R/V KW are plotted in **Fig. 7**. Concurrent ECO VSF measurements are overlaid with circles. The ECO VSF measurements show excellent agreement with the MASCOT data. This is clear when looking at a vertical profile from Hawaii (**Fig. 8**). Preliminary analyses with Fournier-Forand phase function fits have also shown that the measured VSFs may be represented well by a particle population with a Jungian type particle size distribution with low bulk refractive index, although some overestimation at mid-angles is evident. It appears that the combination of two or more such populations may be required to achieve a precise fit, not an unexpected finding.

IMPACT/APPLICATIONS

Progress and results represent important steps toward the development of a multi-angle, in-water VSF device. Knowledge of the Inherent Optical Properties including the VSF can be used to predict and optimize the performance of a host of Naval operations that rely on divers, cameras, laser imaging systems, and active and passive remote sensing systems. These include mine countermeasures, harbor security operations, debris field mapping, anti-submarine warfare, and search and salvage operations. These measurements may also be used in environmental monitoring and research applications for determining particle composition.

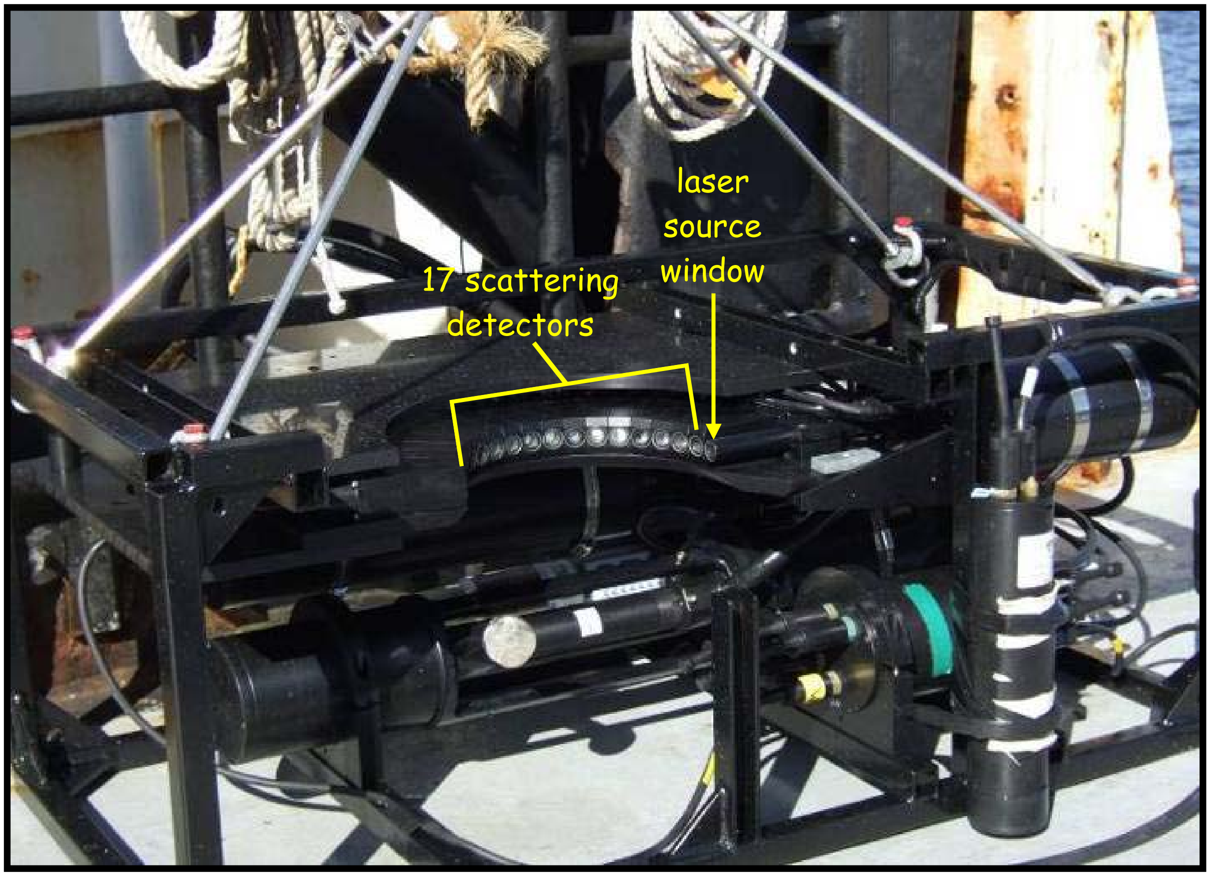

Figure 2. MASCOT VSF device mounted with other optical sensors in a custom cage designed to sample the subsurface domain.

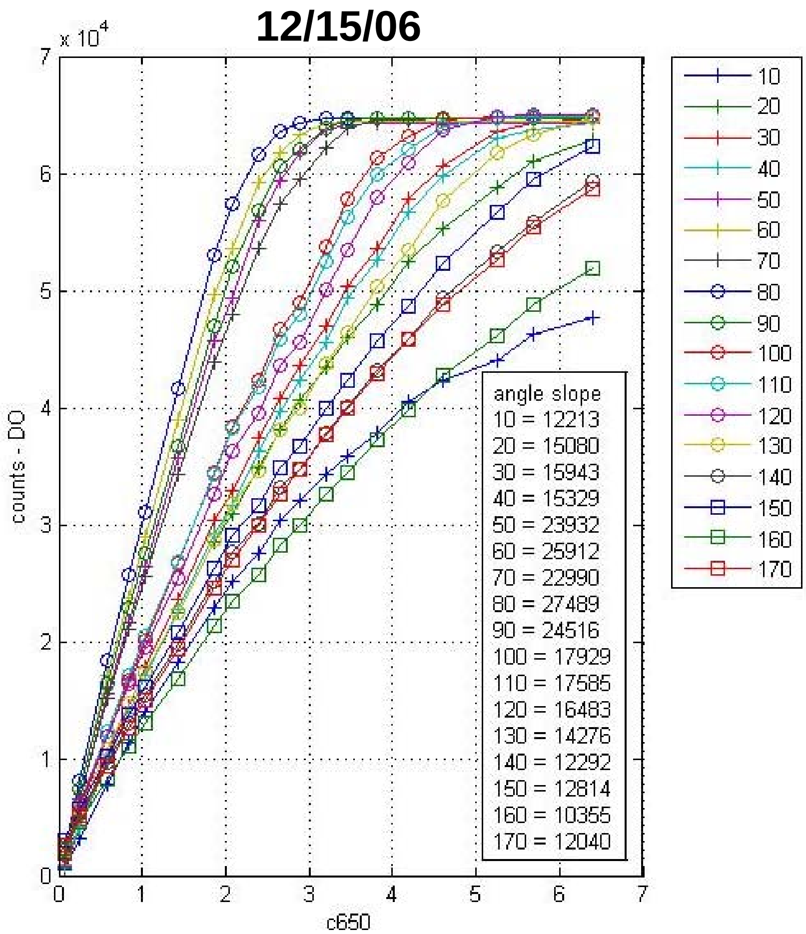

Figure 3. Digital response of MASCOT scattering channels as a function of c(650) measured with an ac-9 in numerous suspensions of AZRD.

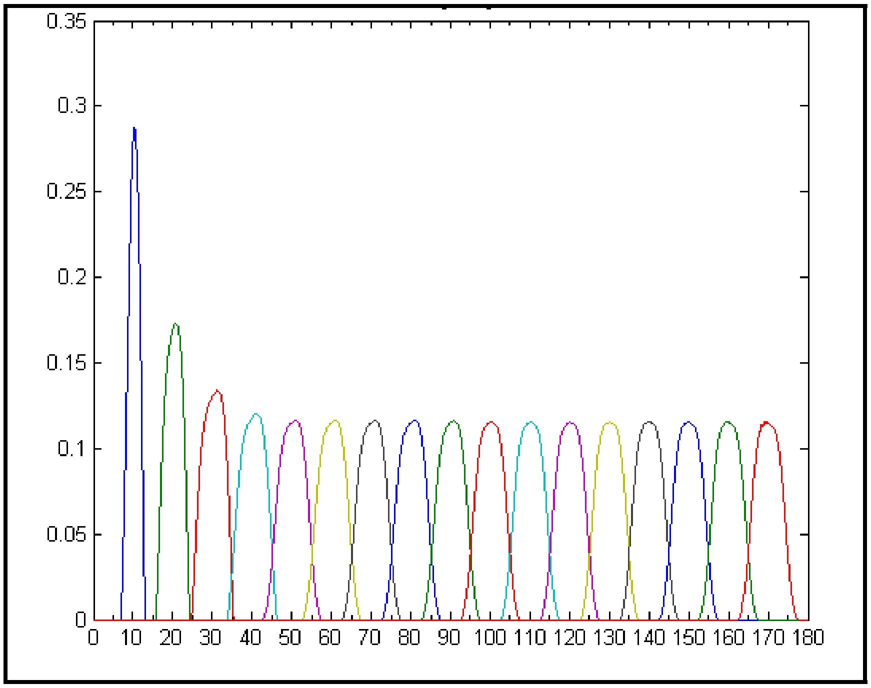

Figure 4. Analytically computed weighting functions for the 17 MASCOT scattering measurements.

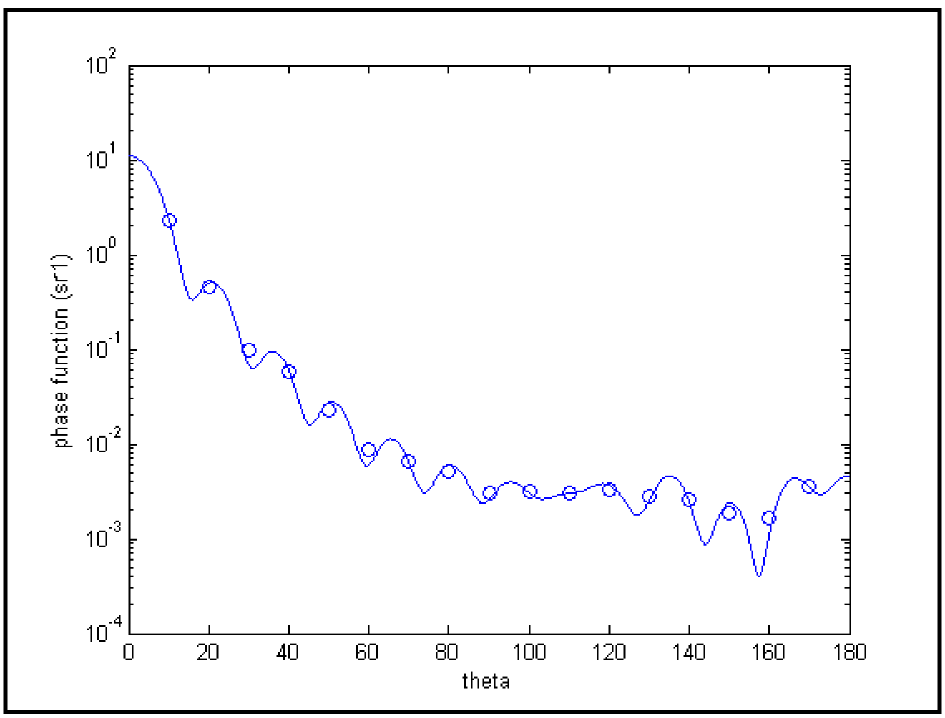

Figure 5. Phase function, $P(\theta)$, of 1.992±0.025 um beads. Circles are values obtained from convolving the phase function with the weighting functions for the MASCOT scattering measurements.

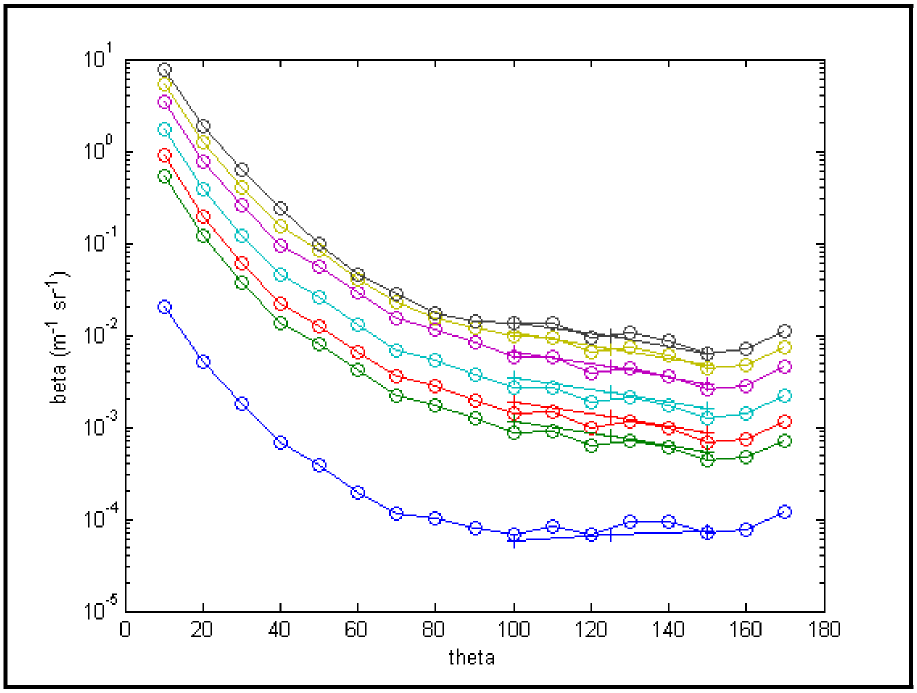

Figure 6. Fully calibrated MASCOT VSFs obtained in suspensions of AZRD. Concurrently collected ECOVSF VSF data are plotted using (+) symbols.

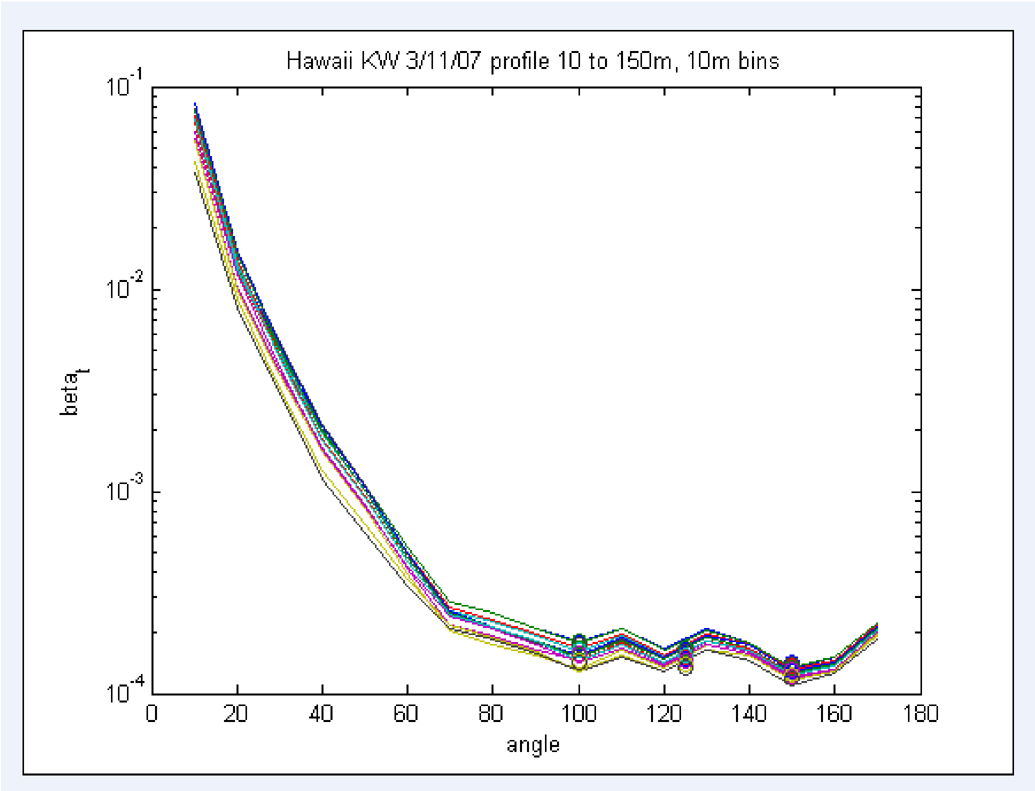

Figure 7. Calibrated MASCOT VSFs obtained in Hawaii. Concurrently collected ECOVSF data are plotted as circles.

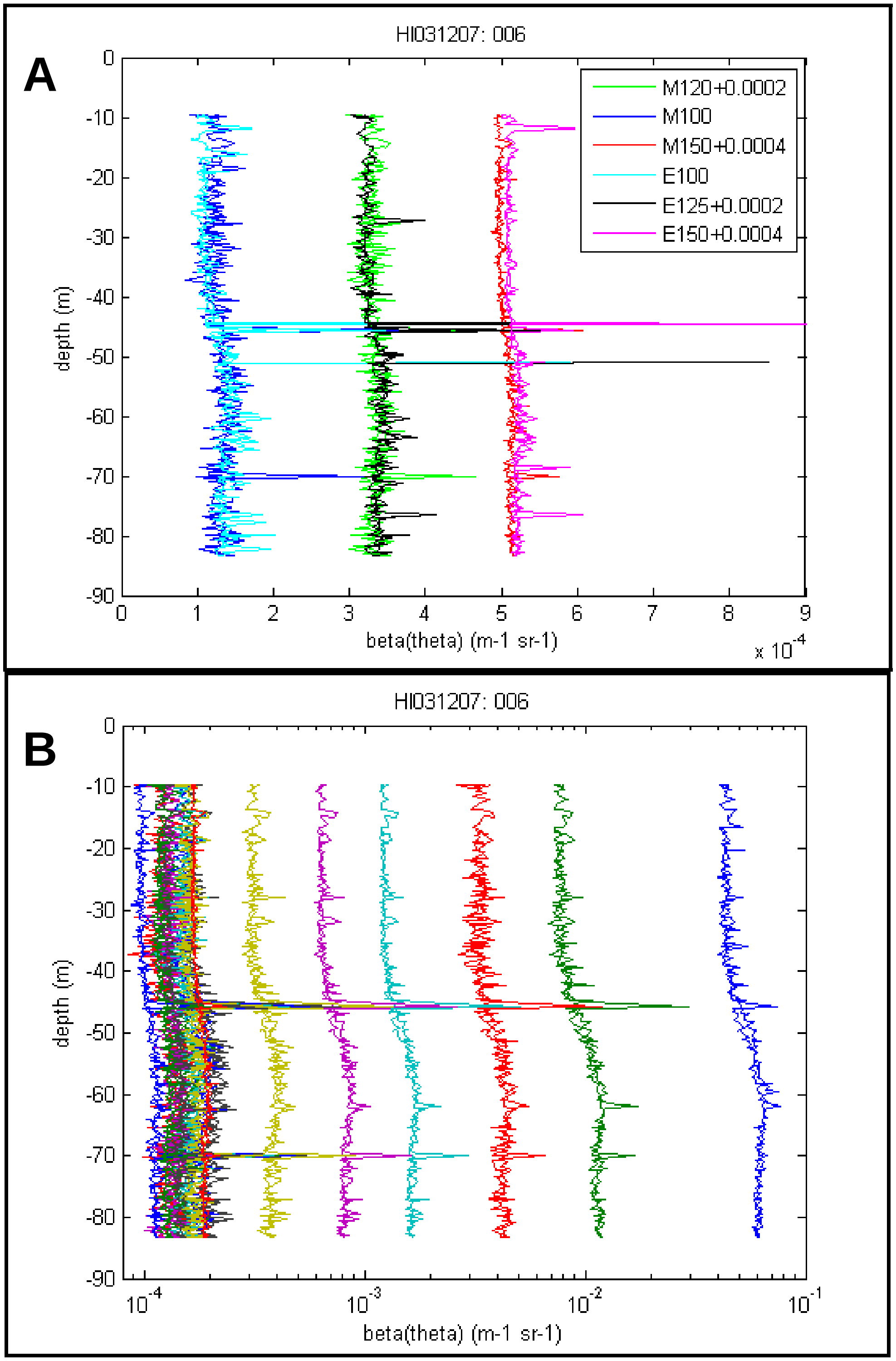

Figure 8. (A) A profile from Hawaii of the 17 $\beta(\theta)$ measured with the MASCOT; (B) selected $\beta(100)$, $\beta(120)$, and $\beta(150)$ measured with the MASCOT and overlaid $\beta(100)$, $\beta(125)$, and $\beta(150)$ concurrently measured with an ECOVSF. The 'M' and 'E' labels in the legend refer to MASCOT and ECOVSF, respectively. Measurements at 120 and 150 degrees are offset by 0.0002 and 0.0004 m^{-1} sr^{-1}, respectively, for clarity. Agreement between the MASCOT and ECOVSF measurements is excellent.

TRANSITIONS

We expect that our efforts in developing an in-water VSF device and associated inversion techniques to better understand particle dynamics in natural waters will lead to transition as operational tools for the fleet and the oceanographic research community in the future.

RELATED PROJECTS

This effort is related to several ongoing efforts to develop optical sensors and associated biogeochemical inversion techniques. Related projects include:

- resolving the optics and dynamics of subsurface bubble populations in the Southern Ocean,

- developing novel harbor security monitoring capabilities with Chuck Trees and Jim Mueller,

- developing improved vicarious calibration and validation methods for ocean color satellite remote sensing,

- investigating the sources of backscattering in natural waters,

- developing tools for ocean observing systems, and

- developing a surfzone optical mine countermeasure drifter.

PUBLICATIONS IN LAST FIVE YEARS

Boss, E., and M.S. **Twardowski**. 2000. On the relationship of the particulate beam attenuation spectrum and size distribution of oceanic particles. *Proceedings from Ocean Optics XV*, October 16-20, Monaco.

Coleman, J.E., R.A. Reynolds, M.C. Talbot, M.S. **Twardowski**, M.J. Perry. 2000. Utilization of solar-induced chlorophyll a fluorescence as an indicator of phytoplankton biomass in coastal waters. *Proceedings from Ocean Optics XV*, October 16-20, Monaco.

Eisner, L., M.S. **Twardowski**, and T.J. Cowles. 2000. In situ spectral absorption (ac-9) measurements as an index of photoprotective/photosynthetic carotenoid ratios. *Proceedings from Ocean Optics XV*, October 16-20, Monaco.

Moore, C., M.S. **Twardowski**, and J.R.V. Zaneveld. 2000. The ECO VSF - A multi-angle scattering sensor for determination of the volume scattering function in the backward direction. *Proceedings from Ocean Optics XV*, October 16-20, Monaco.

Twardowski, M.S., E. Boss, J.B. Macdonald, W.S. Pegau, A.H. Barnard, and J.R.V. Zaneveld. 2000. A model for retrieving oceanic particle composition and size distribution from measurements of the backscattering ratio and spectral attenuation. *Proceedings from Ocean Optics XV,* October 16-20, Monaco.

Twardowski, M.S. 2000. Ocean research in the ocean state. *The Rhode Island State Trooper,* 12(1):107-109.

Boss, E., W.S. Pegau, W.D. Gardner, J.R.V. Zaneveld, A.H. Barnard, M.S. **Twardowski**, G.C. Chang, and T.D. Dickey. 2001. Spectral particulate attenuation in the bottom boundary layer of a continental shelf. *J. Geophys. Res.*, 106(C5):9509-9516. [refereed]

Boss, E., M.S. **Twardowski**, and S. Herring. 2001. Shape of the particulate beam attenuation spectrum and its inversion to obtain the shape of the particulate size distribution. *Appl. Opt.,* 40:4885-4893. [refereed]

Dekshenieks, M.M., P.L. Donaghay, J.M. Sullivan, J.E.B. Rines, T.R. Osborn, and M.S. **Twardowski**. 2001. Temporal and spatial occurrence of thin phytoplankton layers in relation to physical processes. *Mar. Ecol. Prog. Ser.,* **223**:61-71. [refereed]

Twardowski, M.S. and A. Barnard. 2001. Observing the ocean: sensing technology and observation platforms. *Maritimes*, 43(4).

Twardowski, M.S., and P.L. Donaghay. 2001. Separating in situ and terrigenous sources of absorption by dissolved material in coastal waters. *J. Geophys. Res.*, 106(C2):2545-2560. [refereed]

Twardowski, M.S., E. Boss, J.B. Macdonald, W.S. Pegau, A.H. Barnard, and J.R.V. Zaneveld. 2001. A model for estimating bulk refractive index from the optical backscattering ratio and the implications for understanding particle composition in Case I and Case II waters. *J. Geophys. Res.*, 106(C7)*:*14,129-14,142. [refereed]

Gould, R., R. Stavn, M. **Twardowski**, and G. Lamella. 2002. Partitioning optical properties into organic and inorganic components from ocean color imagery. *Proceedings from Ocean Optics XVI*, November 18-22, Santa Fe, NM.

Rines, J.E.B., P.L. Donaghay, M. Dekshenieks, J.M. Sullivan, and M.S. **Twardowski**. 2002. Thin layers and camouflage: hidden *Pseudo-nitzschia spp*. (Bacillariophyceae) populations in a fjord in the San Juan Islands, Washington, U.S.A. *Mar. Ecol. Prog. Ser.*, 225:123-137. [refereed]

Sullivan, J.M., M.S. **Twardowski**, P.L. Donaghay, and S. Freeman. 2002. Particulate bulk refractive index distributions in coastal regions as determined from backscattering ratio measurements. *Proceedings from Ocean Optics XVI*, November 18-22, Santa Fe, NM.

Twardowski, M.S., and P.L. Donaghay. 2002. Photobleaching of aquatic dissolved materials: absorption removal, spectral alteration, and their interrelationship. *J. Geophys. Res,* 107(C8). [refereed]

Twardowski, M.S., J.R.V. Zaneveld, and C. Moore. 2002. A novel technique for determining beam attenuation compatible with a small sensor form factor and compact deployment platforms. *Proceedings from Ocean Optics XVI*, November 18-22, Santa Fe, NM.

Zaneveld, J.R.V., M.S**. Twardowski**, K.S. Shifrin, W.S. Pegau, E. Boss, and I. Zolotov. 2002. Inversion of light scattering measurements to obtain biogeochemical parameters. *Proceedings from Ocean Optics XVI*, November 18-22, Santa Fe, NM.

Dekshenieks, M.M., AL Alldredge, A Barnard, E Boss, J Case, TJ Cowles, PL Donaghay, LB Eisner, DJ Gifford, CF Greenlaw, C Herren, DV Holliday, D Johnson, S MacIntyre, D McGehee, TR Osborn, MJ Perry, R Pieper, JEB Rines, DC Smith, JM Sullivan, MK Talbot, MS **Twardowski**, A Weidemann and JR Zaneveld. 2003. Characteristics, Distribution and Persistence of Thin Layers Over a 48 Hour Period. *Mar. Ecol. Prog. Ser.,* 261:1-19. [refereed]

Eisner, L., M.S. **Twardowski**, and T.J. Cowles. 2003. Relationship between phytoplankton pigment composition and in situ spectral absorption measurements in East Sound, Orcas, Island, WA. *Limnol. Oceanogr.*, 48:632-646. [refereed]

Miller, R., M.S. **Twardowski**, C. Moore, and C. Casagrande. 2003. The Dolphin: Technology to Support Remote Sensing Bio-optical Algorithm Development and Applications. *Backscatter* 14(2):8-12.

Boss, E., W. S. Pegau, M. Lee, M. S**. Twardowski**, E. Shybanov, G. Korotaev, and F. Baratange. 2004. The particulate backscattering ratio at LEO 15 and its use to study particles composition and distribution*. J. Geophys. Res.*, 109, C01014, doi:10.1029/2002JC001514. [refereed]

Moore, C., J. Da Cuhna, B. Rhoades, M.S. Twardowski, J.R.V. Zaneveld, J. Dombroski. 2004. A new in-situ measurement and analysis system for excitation-emission fluorescence in natural waters. *Proceedings of Ocean Optics XVII*, October 25-29, Freemantle, Australia.

Schofield, O., J. Kohut, J. Kerfoot, L. Creed, C. Mugdal, S. Glenn, M. **Twardowski**, C. Jones, and D. Webb. 2004. Dawn in the age of ocean robots: what can they see? *Proceedings of Ocean Optics XVII*, October 25-29, Freemantle, Australia.

Sullivan, J.M., M.S. **Twardowski**, J.R.V. Zaneveld, C. Moore, B. Rhoades, and R. Miller. 2004. The hyperspectral temperature and salinity dependent absorption coefficients of pure water. *Proceedings of Ocean Optics XVII*, October 25-29, Freemantle, Australia.

Twardowski, M.S., and J.R.V. Zaneveld. 2004. Progress toward a Generalized Optical-Biogeochemical Inversion (GOBI) for natural waters. *Proceedings of Ocean Optics XVII*, October 25-29, Freemantle, Australia.

Twardowski, M.S., E. Boss, J.M. Sullivan, and P.L. Donaghay. 2004. Modeling spectral absorption by chromophoric dissolved organic matter (CDOM**).** *Mar. Chem.*, 89: 69-88, doi:10.1016/j.marchem.2004.02.008. [refereed]

Zaneveld, J.R.V., C. Moore, A.H. Barnard, M.S. **Twardowski**, and G.C. Chang. 2004. Correction and analysis of spectral absorption data taken with the WET Labs AC-S. *Proceedings of Ocean Optics XVII*, October 25-29, Freemantle, Australia.

Sullivan, J.M., M.S. **Twardowski**, Donaghay, P.L., and Freeman, S.A. 2005. Using Scattering Characteristics to Discriminate Particle Types in US Coastal Waters, *Appl. Opt*., 44:1667-1680. [refereed]

Trees, C.C., P.W. Bissett, H,. Dierssen, D.D.R. Kohler, M.A. Moline, J.L. Mueller, R.E. Pieper, M.S. **Twardowski**, and J.R.V. Zaneveld. 2005. Monitoring water transparency and diver visibility in ports and harbors using aircraft hyperspectral remote sensing. *Prodeedings from SPIE Port and Harbor Security Conference*, Vol. 5780, February, Orlando, FL.

Twardowski, M.S., M. Lewis, A. Barnard, J.R.V. Zaneveld. 2005. In-water instrumentation and platforms for ocean color remote sensing applications. *In:* Remote Sensing of Coastal Aquatic Waters, R. Miller and C. Del-Castillo [Eds.], Springer-Kluwer Publishing, pp. 69-100. [refereed]

Twardowski, M.S., J.R.V. Zaneveld, C.M. Moore, J. Mueller, C. Trees, O. Schofield, S. Freeman, T. Helble, and G. Hong. 2005. Diver visibility measured with a compact scattering-attenuation meter (SAM) compatible with AUVs and other small deployment platforms. *Prodeedings from SPIE Port and Harbor Security Conference*, Vol. 5780, February, Orlando, FL.

Zaneveld, J.R.V., M.S. **Twardowski**, M. Lewis, and A. Barnard. 2005. Radiative transfer and remote sensing. *In*: Remote Sensing of Coastal Aquatic Waters, R. Miller and C. Del-Castillo [Eds.], Springer-Kluwer Publishing, pp. 1-20. [refereed]

Aurin, D., H. Dierssen, and M. **Twardowski**. 2006. Absorption, Backscatter and Chlorophyll Algorithms for Ocean Color Remote Sensing in Long Island Sound. *Proceedings of Ocean Optics XVIII*, October 9-13, Montreal, Canada.

Sullivan, J.M., M.S. **Twardowski**, J.R.V. Zaneveld, C. Moore, A. Barnard, P. Donaghay, and B. Rhoades. 2006. The hyperspectral temperature and salinity dependencies of absorption by water and heavy water in the 400-750 nm spectral range. *Appl. Opt.*, 45:5294-5309. [refereed]

Twardowski M., and M. Jonasz. 2006. VSF at the small angles for natural dispersions and power-law slopes (www.tpdsci.com/Tpc/VsfSmlAngNatDspSlp.php). In: *Topics in Particles and Dispersion Science* (www.tpdsci.com). [refereed]

Twardowski M., and M. Jonasz. 2006. Power law in spectral scattering by natural dispersions: Derivation (www.tpdsci.com/Tpc/AtnCfSptPwLwNatDsp.php). In: *Topics in Particles and Dispersion Science* (www.tpdsci.com). [refereed]

Twardowski M., and M. Jonasz. 2006. Power law in spectral scattering by natural dispersions: Finite range of the particle diameter (www.tpdsci.com/Tpc/AtnCfSptPwLwNatDsp.php). In: *Topics in Particles and Dispersion Science* (www.tpdsci.com). [refereed]

Zaneveld, J.R.V, M.S. **Twardowski**, and C. Moore. 2006. Total scattering coefficient meter. *Proceedings of Ocean Optics XVIII*, October 9-13, Montreal, Canada.

Hout, Y., M. Babin, F. Bruyant, C. Grob, M. S. **Twardowski**, and H. Claustre. 2007. Does chlorophyll *a* provide the best index of phytoplankton biomass for primary productivity studies? *Biogeosciences*, in press.

Babin, M., D. Stramski, D. Marie, C. Grob, A. Sciandre, R.A. Reynolds, O. Ulloa, D. Vaulot, M. **Twardowski**, and H. Claustre. 2007. Bacscattering properties of natural picoplankton populations obtained by flow cytometry sorting of open ocean water samples. *Biogeosciences*, submitted.

Dombroski, J., and M.S. **Twardowski**. 2007. Identification of Fluorophoric Components of Dissolved Organic Matter in Narragansett Bay, Rhode Island Using Excitation-Emission Matrices and Parallel Factor Analysis (PARAFAC). *Science of the Total Environment*, submitted.

Stramski, D., R. Reynolds, M. Babin, H. Claustre, S. Kaczmarek, M. Lewis, R. Rottgers, A. Sciandra, M. Stramska, and M. **Twardowski**. 2007. Relationships between the particulate organic carbon concentration and optical properties of surface waters in the South East Pacific and Atlantic Oceans. *Biogeosciences*, in review.

Twardowski, M.S., H. Claustre, S.A. Freeman, D. Stramski, and Y. Hout. 2007. Optical backscattering properties of the "clearest" natural waters. *Biogeosciences*, in review.

PATENTS

Scattering attenuation meter (SAM), pending.

HONORS/AWARDS/PRIZES

Twardowski, M., 2005: *Spinoff* technology selection, NASA Innovative Partnership Program, http://www.sti.nasa.gov/tto/Spinoff2005/PDF/accessible.pdf, p. 62.

Twardowski, M., 2003: Adjunct Professor, University of Rhode Island.

Twardowski, M., 2000: ASEE Visiting Faculty Fellowship, Naval Research Labs.

Twardowski, M., 2000: Early Career Faculty Award, Office of International Research and Development, Oregon State University.

Twardowski, M., 1998: WET Labs Environmental Optics Postdoctoral Fellowship, Oregon State University.